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MISCELLANEOUS PAPER M-72-4

EFFECTS OF ENVIRONMENT ON SEISMIC INTRUSION DETECTOR PERFORMANCE

A PRELIMINARY REPORT

by

B. O. Benn, L. E. Link

April 1972

Sponsored by U. S. Army Engineer Topographic Laboratories, Fort Belvoir, Virginia

Conducted by U. S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi

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ARMY-MRC VICKSBURG, MISS

FOREWORD

The model development work reported herein is in support of Task 1186004006 of the Geographic Sciences Division, U. S. Army Engineer Topographic Laboratories (ETL), project entitled "Military Geographic Intelligence (MGI) Products to Support Battlefield Sensor Activities." The objective of the project is to design a family of prototype military geographic intelligence products to support planning for the use and operational placement of ground-contact sensors on a battlefield to detect the presence of enemy troops and equipment.

The U. S. Army Engineer Waterways Experiment Station (WES) contribution to the MGI project depended heavily on data collected in a number of seismic sensor programs. Acknowledgment is given for data furnished by Project MASSTER, Defense Special Projects Group (DSPG), the U. S. Army Test and Evaluation Command, and the Office, Chief of Engineers.

The work reported herein is the result of a coordinated effort during the period 1 January-30 June 1971 by members of the Terrain Analysis Branch, Mobility and Environmental (M&E) Division; the Soil Dynamics and Geology Branches, Soils Division; and the Operations Branch, Instrumentation Services Division. Key participants in the study were Messrs. Bob O. Benn and L. E. Link of the Terrain Analysis Branch and Mr. Robert F. Ballard and Dr. William F. Marcuson of the Soil Dynamics Branch. The report was prepared by Messrs. Benn and Link.

The study was under the direct supervision of Mr. Benn, the Program Manager, and under the general supervision of Mr. W. E. Grabau, Chief, TAB, and Messrs. W. G. Shockley and S. J. Knight, Chief and Assistant Chief, respectively, of the M&E Division. The Director of the WES during the study period was COL Ernest D. Peixotto, CE. The Technical Director was Mr. F. R. Brown.

CONTENTS

SUMMARY

Improved guidance manuals for planning the deployment and emplacement of seismic intrusion detectors (SID's) are needed to optimize the use of these devices for battlefield surveillance. The development of these Military Geographic Intelligence (MGI) products requires a detailed understanding of the operating principles of the detector coupled with an equally detailed understanding of the interactions of the sensor propagation mode with the operational environment. This report presents the results of a preliminary analysis of data collected in a wide range of environments at 22 sites in Panama, 10 sites in Puerto Rico, 6 sites near Yuma Proving Ground, Arizona, and 9 sites near Ft. Huachuca, Arizona.

Multiple regression techniques were used to determine the terrain factors that could be correlated with the seismic responses resulting from a man walking or a controlled source (drop hammer) that simulated the signature resulting from a footstep. The measure of seismic response was peak particle velocity as a function of distance from the source. The terrain factors that correlated best with peak particle velocity were the thickness of the first refraction layer, cone index of the 0- to 15-cm soil layer, dry density of surface soil and first soil layer, water content of surface soil and first soil layer, compression wave velocity, Rayleigh wave velocity, and grain-size distribution. An empirical equation was developed to predict peak particle velocity versus distance as a function of the terrain factors. The particle velocities required to trigger the logic of the Phase III SID's were superimposed on the predicted peak particle velocity curves to arrive at a prediction of sensor performance. These computation procedures were computerized to make a prediction model for relative SID performance as a function of terrain factor values.

The empirical prediction equation adequately predicted the peak particle velocity-distance relation; however, the predictions of sensor performance were inadequate. The errors in the predictions of sensor performance were attributed to the inadequacy of the peak particle velocity-distance relation to represent the complex interaction of the entire seismic signal and the sensor. Frequency characteristics of the seismic signal and the frequency response characteristics of the sensors also must be considered.

EFFECTS OF ENVIRONMENT ON SEISMIC INTRUSION DETECTOR PERFORMANCE

PART I: INTRODUCTION

Background

1. The urgent need for battlefield surveillance devices has prompted the rapid development of seismic and other sensor hardware that have proven useful in a number of combat situations in South Vietnam. Unfortunately, success stories cannot be written for all sensor deployment attempts. A major factor recognized as responsible for the less than outstanding performance of the devices (Military Geographic Intelligence (MGI) products) is the lack of adequate guidance manuals for planning their deployment and emplacement. Attempts to fill this gap have not been successful because the production of such manuals requires a detailed understanding of the operating principles of the detectors coupled with an equally detailed understanding of the interactions of the sensor propagation mode with the operational environment. Considerable development work is known to be needed before rational procedures for producing MGI products for all types of sensor systems can be formulated. For example, although this effort has been restricted to seismic intrusion detectors (SID's), the results have to be considered interim solutions until more definitive work can be completed.

2. The operating principles of SID's are reasonably well known; however, the manner in which the seismic energy is transferred from the source (vehicle or persons) to the ground, the way the substrate conditions affect the energy propagation, and the manner in which the energy is transferred from the ground to the sensor geophone are not understood. Theoretical solutions to these problems are and have been the partial objectives of considerable research sponsored by the Department of Defense. The results of current research in this area being conducted at the U. S. Army Engineer Waterways Experiment Station (WES) for the Office, Chief of Engineers (OCE), and the Defense Special Projects

Group (DSPG) are encouraging; nevertheless, a practical theoretical solution will require additional research.

3. Work on the projects mentioned above and other related efforts have resulted in the collection of considerable data that are available for empirical analysis. Some analysis has been accomplished and an equation has been formed that allows prediction of seismic signal levels as a function of distance from a source. This equation has been coupled with seismic sensor performance specifications to formulate an interim sensor performance prediction model.

4. Specific and quantitatively defined terrain factors are the inputs to the interim model. To obtain these inputs easily from conventional terrain intelligence gathering techniques would be desirable; but not all the present terrain inputs can be so obtained, and transforms must be found.

5. The equation used in the interim prediction model has been derived from the analysis of data collected in a wide range of environments, i.e. Puerto Rico, Panama, and Arizona. Additional data will be collected and the prediction model improved as the data are analyzed. The interim model has been designed so that modifications can be made easily as new data or theoretical information becomes available.

Purpose and Scope

6. The purpose of the study reported herein was to provide technical assistance to the U. S. Army Engineer Topographic Laboratories (ETL) seismic sensor MGI product project by developing theoretical relations of seismic wave propagation in earth media and empirical relations based on the analysis of existing terrain/sensor data.

7. The report includes a brief discussion of the seismic and environmental field data collection programs, and data reduction and analysis procedures followed in the development of a seismic sensor performance model. Techniques for measuring or estimating the terrain factor inputs to the model are also discussed.

8. Existing theoretical solutions were found to be in a form not

directly compatible with the project objective. They were used extensively, however, in the design of the data collection, reduction, and analysis procedures used in the development of the model.

Definitions

9. Certain terms pertinent to this study and having restricted meaning are defined below.

Cone index.[1] An index of the shearing resistance of a medium obtained with the cone penetrometer. The value represents the resistance of the medium to penetration of a 30-deg cone of 0.5-sq-in. (6.45-cm^2) base or projected area. The number, although usually considered dimensionless in trafficability studies, actually denotes pounds of force on the handle divided by the area of the cone base in square inches. The cone index of the soil surface and the average cone index of the 0- to 15-cm layer are used in this report.

Dry density (γ_d).[1] Dry unit weight; the weight of oven-dried soil solids (W_s) from a sample per unit of total volume (V_T) of the soil sample. Symbolically this is

$$\gamma_d = \frac{W_s}{V_T} (\text{in g/cm}^3)$$

Particle velocity. The time rate of change of the motion of a particle of the medium with respect to a specified reference frame. The particle velocity was measured by the geophones used in this study.

Water content (w).[1] The ratio of the weight of water (W_w) in a sample of soil to the weight of soil (solids only) (W_s) in the same sample expressed as a decimal. It may be written as

$$w = \frac{W_w}{W_s}$$

Compression wave velocity (Vp). The speed of a compression wave through a medium. Compression waves have the greatest velocity of any elastic wave in the same medium. The motion of the particles is

parallel to the direction of propagation. V_P is defined mathematically as

$$V_P = \sqrt{\frac{\lambda + 2G}{\rho}}$$

where

V_P = compression wave velocity, LT^{-1}

λ = Lame's constant, $ML^{-1}T^{-2}$

G = shear modulus, FL^{-2}

ρ = mass density, $GL^{-4}T^{2}$

Rayleigh wave velocity (V_R). The speed of a Rayleigh wave (particle motion is elliptically retrograde and parallel to the direction of propagation) along the free surface of a medium; depends on Poisson's ratio (ν) of the medium. For values of Poisson's ratio $0<\nu<0.5$, the Rayleigh wave velocity has the range $0.875V_S < \nu_r < 0.955V_S$, where V_S = shear wave velocity.

Shear wave velocity (V_S). The speed of a shear wave (particle motion of the medium is perpendicular to the direction of propagation) through a medium, defined mathematically by the equation

$$V_S = \sqrt{\frac{G}{\rho}}$$

where

V_S = shear wave velocity, LT^{-1}

G = shear modulus, FL^{-2}

ρ = mass density, $GL^{-4}T^{2}$

Thickness of the first soil layer (H_1). The vertical depth (i.e. perpendicular to the surface) to the interface between the surface layer and the next shallowest layer as distinguished by their differing primary wave velocities. The primary wave velocities of these two layers are determined by techniques of refraction seismology. (Note: The above-defined layers often, but not necessarily, correspond to soil layers as defined by nonseismic parameters (e.g. grain size, density, etc.).)

PART II: DERIVATION OF TERRAIN/SENSOR INTERACTIONS

Field Data Collection Program

10. The ETL seismic sensor study utilized data collected in the conduct of related seismic sensor research. The field data collection program was designed to provide information for development of empirical terrain/seismic response relations and to verify theoretically developed relations. The approach used was to perform special seismic tests in various environmental conditions, collect environmental data concurrently with the seismic tests, and then study these data to determine empirically the effects of environment on seismic response. This part of the report discusses the field data collection program, derivation of particle velocity/environment/distance relations and the manner in which the relations were coupled with Phase III sensor logic[2] to provide a capability for predicting an indicator of sensor performance. Phase III sensors are the most recently developed SID's; the sensor development program be-an with the Phase I sensors and has since moved through the Phase II sensors into the development of improved devices that are designated Phase III sensors.

Site selection

11. To ensure that tests were conducted in a wide range of environmental conditions, care was taken in selecting sites within predetermined study areas. Field work was accomplished at 22 sites in Panama, 10 sites in Puerto Rico, and 15 sites in Arizona. The sites were tentatively selected in the office by utilization of available published data, topographic maps, and air photos. The published data and maps were used to supplement a photo interpretation study that involved a stereoscopic examination of the photos of the study area. Photo patterns were isolated on the basis of their tone, texture, and shape; and the assumption was made that each discrete pattern represented a certain combination of environmental conditions. Sites were tentatively selected to encompass as many of the terrain conditions as possible within a study area; however, accessibility to a site

was also taken into consideration.

12. The final selection of sites was not made until after a ground reconnaissance was performed to determine the validity of the assumptions made during the office study. Soil, surface geometry, and vegetation conditions were observed at the tentative sites. Other areas were also visited to see if different conditions existed that were not recognized during the photo interpretation study. Upon completion of the ground reconnaissance, the final site selections were made.

Site layout

13. To perform the seismic tests, each site was prepared in a specific manner. A walk path was laid out 60 m long, with the 0- station located in the middle and stakes at 5-m intervals along the entire length of the path. Another line of the same length was laid out perpendicular to the first and intersecting it 2 m from the 0-station. Stakes also were placed at 5-m intervals along the second line. Fig. 1 shows a typical site layout.

Environmental data

14. All of the environmental factors that were hypothesized to affect the seismic response of the area were considered. The following environmental descriptors were believed to be important, and information was collected on each either by direct measurement, laboratory analysis, or computation.

a. Soil characteristics

(1) Layer thickness (refraction seismic technique)

(2) Moisture content

(3) Dry density

(4) Void ratio

(5) Degree of saturation

(6) Liquid limit

(7) Plastic limit

(8) Cone index

(9) Grain-size distribution

b. Vegetation characteristics

(1) Stem diameter

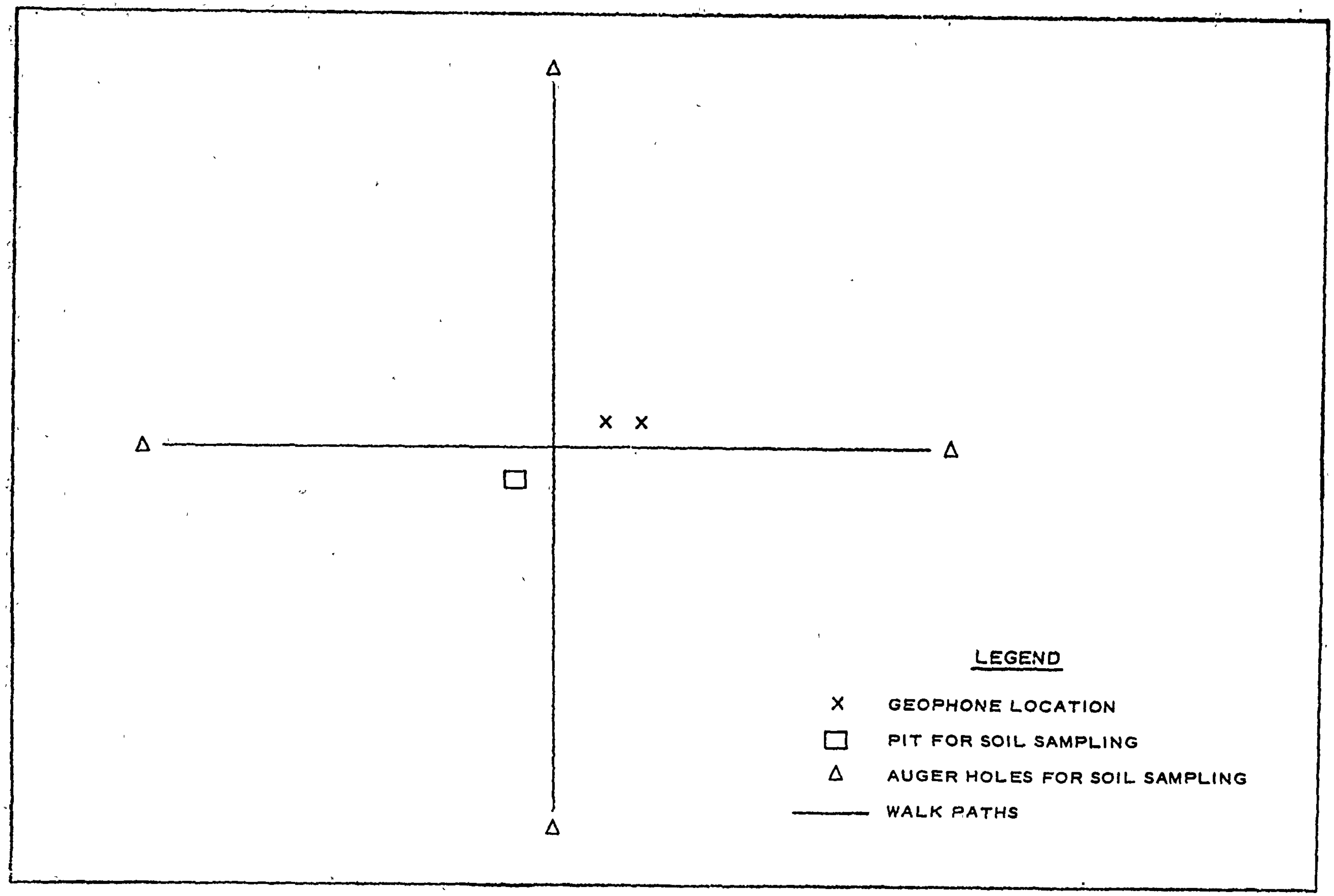

Fig. 1. Typical site layout

(2) Stem height

(3) Stem spacing

(4) Crown volume

c. Surface geometry: surface profiles

d. Meteorological conditions

(1) Wind speed

(2) Wind direction

(3) Rainfall

(4) Air temperature

(5) Soil temperature

15. The soils data were obtained by measuring the basic soil parameters in the field with such devices as a nuclear moisture-density meter, and by using conventional soil sampling procedures and obtaining values through laboratory analysis of the samples. The vegetation and surface geometry data were collected according to standard WES procedures. Meteorological data were obtained with instrumentation available at the test sites or with a portable field unit designed at the WES.

16. Techniques for measurement or calculation of the terrain factor values have been extensively documented in the references listed at the end of the text of this report. Up-to-date instrumentation and techniques were used, and the data were recorded in formats compatible with automatic data processing that allowed their efficient analysis. Complete documentation of the field data collection program will be published as part of a report[3] dealing with a related seismic sensor program.

Seismic response data

17. The seismic response data were collected at the various locations by measuring the particle velocity resulting from (a) a man walking and (b) a controlled energy source (hammer drop). The seismic responses were measured with two, three-directional geophones and recorded on magnetic tape with a wide-band amplifier-recorder system. The geophones, moving-coil type with a usable flat frequency response from 1.5 to 200 Hz, were buried flush with the ground surface and 5 m apart,

positioned as shown in fig. 1. The drop-hammer energy source was designed with the hope that its response would be comparable in magnitude and signature to the response produced by a footstep. Since footsteps are very variable in character, the particle velocity resulting from the hammer drop would hopefully allow a more accurate comparison of seismic responses in various environmental conditions.

18. In the man-walking tests a man walked at a constant rate along both prescribed paths. He started 30 m from the centermost geophone array, and continued on the same line until he was 30 m past the centermost array, which brought him to within 2 m of the centermost array on each path. The controlled-source (drop-hammer) tests were conducted by dropping the calibrated weight of the hammer at 5-m intervals along the same paths used for the walk tests.

19. The peak particle velocity, or maximum signal amplitude, resulting from each footstep or hammer drop was obtained from the magnetic tape recordings by machine processing at the WES. These data were used to develop peak particle velocity-distance relations. (The data collected in Puerto Rico were recorded on oscillographs and were reduced manually to obtain the peak particle velocity values for the Puerto Rico sites.)

Derivation of Equations

Regression technique

20. The data collected in the field in Panama, Puerto Rico, and Arizona were used as a base for generating an empirical equation describing the seismic response. The dependent variable selected for this study was the peak particle velocity resulting from the calibrated (drop-hammer) source. The independent variables consisted of the various descriptors of the soil characteristics (paragraph 14), combinations of soil descriptors, functions relating the soil descriptors, and various combinations of all of the above.

21. To formulate a peak particle velocity-distance prediction capability, a basic format had to be selected for use in developing

the empirical equation. The best results were believed to be obtainable if the empirical equation format conformed closely to theoretical considerations of seismic energy decay with distance. Two types of decay were considered, geometric damping and equivalent viscous damping. Geometric damping, the decay of energy due to the spreading of the wave front over a larger and larger volume, for a Rayleigh wave can be described by $1/\sqrt{r}$, where r is the distance from the source.[4] Equivalent viscous damping can be approximated by an exponential decay function and has been described by the expression [5]

$$e^{-\left(\frac{k'W}{2\pi V_R}\right) r}$$

where

e = base of natural logarithm

k' = damping coefficient

W = mean circular frequency

V_R = Rayleigh wave velocity

r = radial distance from source

22. A similar expression was chosen for the empirical analysis:

$$\frac{Ae^{-\alpha r}}{\sqrt{r}}$$

where $1/\sqrt{r}$ describes the geometric damping of the Rayleigh wave, and $e^{-\alpha r}$ conforms to the equivalent viscous damping of the wave, with α replacing $(k'W)/(2\pi V_R)$ used in the theoretical expression. The A term represents an initial particle velocity amplitude that is attenuated by the $e^{-\alpha r}/\sqrt{r}$ expression. In theoretical work, the A term comprises a number of functions that theoretically describe an unattenuated Rayleigh wave. In this case, α is somewhat similar to the equivalent viscous damping coefficient, although it includes the other terms in the total coefficient of the theoretical equation. For the purpose of this study, α was considered to be a constant over the frequency range of the data since a large range in frequencies did not occur.

Description of computer software

23. A multiple regression computer program written by Mr. J. H Goodnight of North Carolina State University, Raleigh, North Carolina, was utilized to correlate the independent variables and combinations thereof with the dependent variable. In general, use of the computer program entails four basic steps:

a. Values for the basic variables are fed in, and values for the combined variables are generated.

b. The simple statistics (i.e. sum, mean, sum of squares, variance, and standard deviation) of each variable are computed; and a bivariant analysis is conducted, i.e. each variable is correlated with every other variable, one at a time. This indicates the variables that are interrelated.

c. A model is built for each specified dependent variable. The computer searches the independent variables (first taking one at a time, then two at a time, and so on) and lists the individual variables that correlate best with the dependent variable. These lists of variables are termed models.

d. Based on the models generated, the independent and dependent variables are specified, and the computer uses a Doolittle matrix inversion technique to generate the regression equation of best fit through the data. This equation is in the form

$$Y = B_o + B_iX_i + B_2X_2 \ldots + B_NX_N$$

where

Y = dependent variable

X_i = independent variables

B_i = regression coefficients

24. The correlation coefficient R is defined and used as a measure of "goodness to fit." $R = 1$ is a perfect correlation; whereas $R = 0$ indicates no correlation at all. An analysis of variance table also is printed out for determining the significance of the equations.

Use of computer program

25. The relations between seismic response and environmental factors have been shown to be very complex. To use the strength of the

multiple regression technique to best advantage, a step-by-step procedure for building the desired relations from the basic parameters had to be followed:

a. The basic environmental parameters and simple combinations thereof were correlated with a given seismic response dependent variable to determine the parameters that correlated best with the dependent variable.

b. Equations were written for the best models developed.

c. The equations were used to determine whether the variables were positive or negative with respect to the value of the dependent variable. If the independent variable appeared in a negative term of the equation, it was considered negative; if the independent variable appeared in a positive term in the equation, it was considered positive.

d. The negative and positive variables were then condensed to generate new combined variables. Negative variables were always in the denominator of the new variables, or as negative terms; whereas the positive variables were always placed in the numerator of the new variables, or as positive terms.

e The basic parameters and the newly generated combined variables were again correlated with the dependent variable to improve the correlation.

f. Equations were written for the best models, and the statistics of the equations were evaluated to determine whether further development was required.

g. If further development was required, a third group of combined variables were derived from the newly written equations, and the cycle was continued until no additional improvements could be made.

Peak particle velocity relation

26. The relation between peak particle velocity and the environmental factors was developed in two major phases, both of which followed the steps in the procedure outlined above. The first phase was concerned with the development of relations for A and α. Once these relations were determined, the total relation for peak particle velocity, $Ae^{-\alpha r}/\sqrt{r}$, was developed:

$$\dot{U}\ \text{peak} = 0.11 + \frac{Ae^{-\alpha r}}{\sqrt{r}}$$

where

$$A = 8.31 - 6.02\gamma_{ds} + 17.65 \frac{H_1^2}{V_{pl}^2}$$

$$- 1.118 \frac{H_1^3}{V_{pl}^2 CI_{0-15}} - 4.76 \frac{\left[\gamma_{ds} W_s/(1.0 - \gamma_{ds}/2.65)\right] H_1^4}{V_{pl}^4}$$

$$+ \frac{0.0125}{(1.0 - V_R/V_{pl})\left[\gamma_{ds} W_s/(1.0 - \gamma_{ds})/2.65\right]} ;$$

$$\alpha = -0.169 + 0.000157H_1 + 0.026(1 + W_s)\gamma_{ds}$$

$$+ 0.092(1 + W_1)\gamma_{d1} - \frac{0.000000004 H_1 V_R}{(\%\ \text{fines})_s W_1}$$

$$- 0.0062 \frac{\left[\gamma_{ds} W_s/(1.0 - \gamma_{ds}/2.65)\right] H_1^4}{V_{pl}^4}$$

$\dot{U}_{peak}$ = particle velocity resulting from the hammer drop, cm/sec x 10^{-3}

r = radial distance of source from the geophone, m

H_1 = thickness of first soil layer, m

W_s = moisture content of the surface soil, percent

W_1 = moisture content of the first soil layer,* percent

γ_{d1} = dry density of the first soil layer,* g/cm^3

γ_{ds} = dry density of surface soil, g/cm^3

CI_{0-15} = cone index for the 0- to 15-cm surface soil layer,* psi

e = base of natural logarithm

$(\%\ \text{fines})_1$ = grains finer than 0.074 mm by weight for first soil layer,* percent

V_{pl} = compression wave velocity of first soil layer, m/sec

V_R = Rayleigh wave velocity, m/sec

27. A number of standard statistical tests were used to evaluate the empirical equation. An analysis of variance was performed for the

* Average for the layer.

dependent variable, $\dot{U}$ peak, of the equation and the resulting variance ratio F was tested at the 0.01- and 0.05-levels of significance. The F test showed the equation to be significant at the 0.01 level. A student's t-test, associated with the hypothesis that the regression coefficients are equal to zero, was applied to the coefficients of the regression equation. The results of the t-test showed the coefficients to be nonzero and therefore statistically valid at the 0.01-significance level.

28. The correlation coefficient R of the equation is 0.83. This indicates that the regression equation can be used to predict the peak amplitude of a seismic signal with some degree of precision. The standard deviation σ of the equation is 0.77×10^{-3} cm/sec, which is very significant with respect to the measured values of peak particle velocity at distances greater than 30 m. This indicates that the developed equations will yield predictions that will exhibit considerable scatter.

Prediction of Sensor Performance

Seismic sensor characteristics

29. A schematic drawing of the major components of a seismic sensor is shown in fig. 2. The ground motion resulting from a seismic wave is measured by the geophone and converted into an analog electrical signal. The frequency and amplitude of the electrical signal are proportional to the particle velocity. The electrical signal from the geophone is then fed through a band-pass amplifier, where the signal is filtered and amplified. From the amplifier the signal goes to the sensor logic. If the signal has an amplitude above a certain threshold value, the logic will be activated. The logic will then integrate succeeding signals from succeeding footsteps until enough energy is compiled to reach a second threshold, which causes the sensor to transmit a coded RF signal to a receiving station, indicating that a source of seismic signals, such as a man walking, is nearby.

30. It must be emphasized at this point that the signal reaching

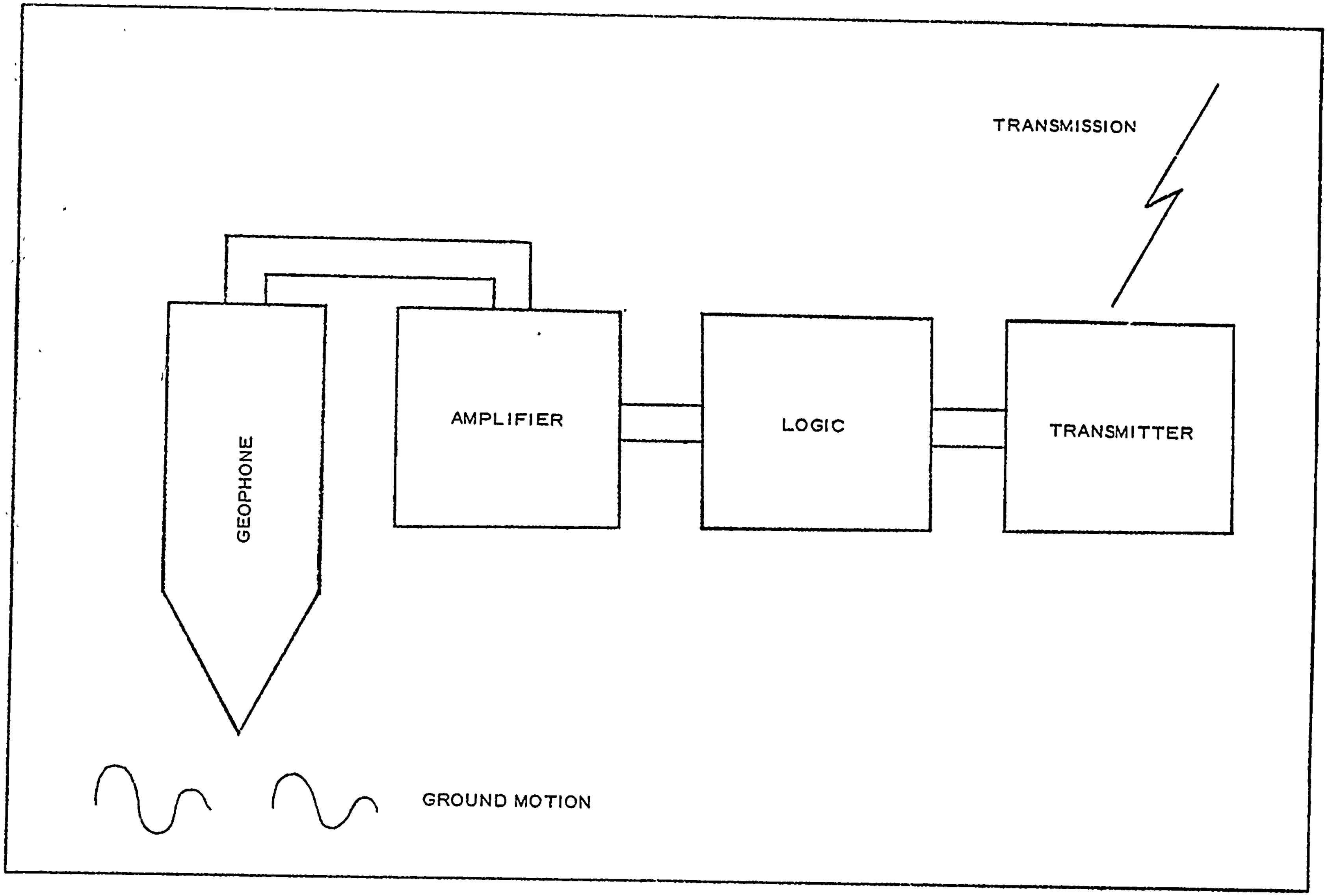

Fig. 2. Schematic of seismic sensor

the logic is very dependent on frequency. The response of the sensor geophone is not constant for all frequencies, and the band-pass amplifier attenuates signals above and below 40 and 0 Hz, respectively. Thus the characteristics of the signal reaching the sensor logic may or may not be directly analogous to the frequency and amplitude of the ground motion.

31. For this preliminary study the effects of signal frequency have been ignored completely, and the signal amplitude reaching the sensor logic has been assumed to be equivalent to the peak particle velocity. The values used for sensor logic thresholds are nominal values based on design specifications. The actual threshold values in the field sensors may vary considerably from one sensor to another because of the wide tolerance in the manufacturing specifications imposed to limit unit costs.

Technique for prediction of sensor performance

32. The empirical equation derived by the multiple regression technique has been combined with nominal values of sensor logic thresholds to provide the capability for predicting sensor performance, as shown in fig. 3. The equation is used to predict the curve of peak

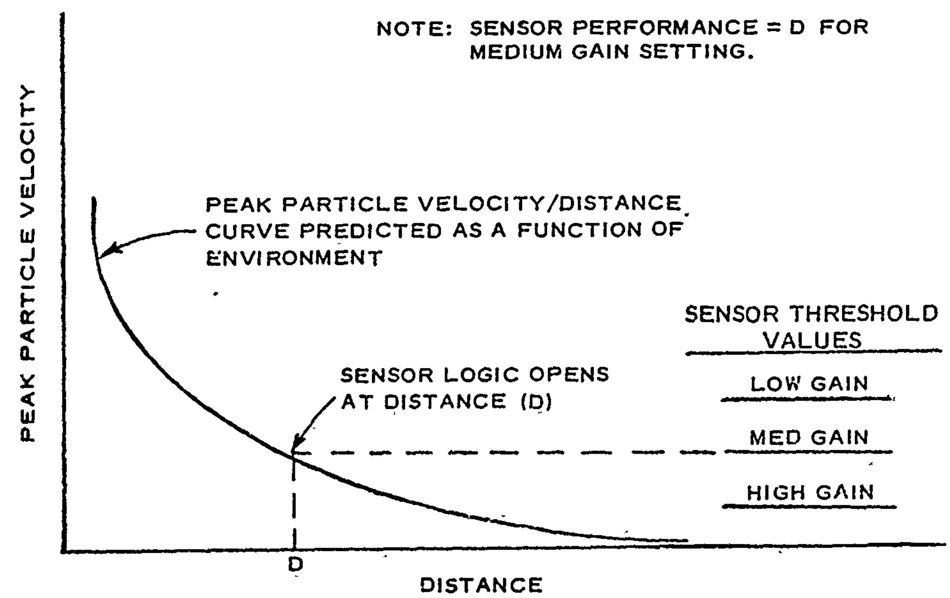

Fig. 3. Generalized relations showing how sensor performance can be predicted

particle velocity versus distance for a given set of environmental conditions. Nominal sensor logic threshold values for high, medium, and low gain are superimposed on the predicted curve; the distance D , where the threshold value for any particular gain intersects the peak particle velocity curve, is the measure of seismic sensor performance for that gain. This technique has been computerized to provide an automated performance prediction capability. The computer program is presented and discussed in detail in Appendix A.

Evaluation of Prediction Capability

33. The primary factor affecting the sensor performance predictions is the accuracy of the predicted particle velocity-distance data, i.e. the adequacy of the regression equation discussed previously.

Adequacy of regression equation

34. The accuracy of the regression equation depends on the closeness of fit of the regression equation to the actual particle velocity-distance data measured in the drop-hammer tests. Predicted and measured peak particle velocity data for selected sites in Panama and Yuma Proving Grounds are compared in plates 1-3. In a majority of cases the predicted values compare closely with the measured data. Much more error occurs in the near-field portion of the plot than in the far-field portion (i.e. at distances greater than 10 m). These plots demonstrate that the multiple regression prediction equation is a fairly good predictor of peak particle velocity for distances greater than 10 m.

Significance of predictions

35. The computer program in Appendix A was used to obtain prediction for medium- and low-gain detection ranges for 19 sites in Panama and Yuma Proving Grounds. To evaluate the adequacy of these predictions for representing the detection distance for a man walking, a body of reference data from which comparisons could be made was necessary. A portion of the necessary reference data was available in the form of one man walking in the detection ranges for a DSID Phase III sensor at low gain for each test site in Panama. A total of five tests

were made at each site. The data were collected concurrently with the field data collection program in Panama; however, they were not considered adequate since they contained a large amount of scatter that could not be explained. To complete the necessary body of reference data, detection distances were determined with an analog computer.

36. A model of a Phase III seismic intrusion detector[2] with PID logic was programmed on an analog computer to form a synthetic sensor, and the measured analog records from the man-walking tests were used as inputs to the model. Detection ranges for one man walking were obtained for both medium and low gains. No attempt was made to predict detection ranges associated with the high-gain setting because background seismic noise levels at every site thus far visited in this program have exceeded the threshold value for high gain. In many cases the background noise level also exceeded the medium-gain threshold.

37. The assumption was that the detection ranges predicted with the analog computer would have higher values and exhibit less scatter than those measured in the field. The measured analog records were obtained with carefully controlled experimental procedures designed to minimize the effects of variation in individual footsteps and walking speeds as well as the energy loss from the soil to the geophone. The detection range measured with the DSID more closely simulated field deployment conditions. Therefore, only occasionally would the DSID-measured detection range be as great as those predicted with the analog computer. The detection ranges obtained from the computer were plotted versus measured detection distance for low gain (fig. 4). In most cases the computer-predicted detection ranges compared well with the maximum measured detection ranges and, with one exception, were greater than the average detection range. In 12 of 16 comparisons the computer predictions were within 5 m of the maximum of the measured data.

38. Perhaps more significant than the approximate one-to-one correspondence of the predicted and maximum measured data is the fact that the range of distance obtained by both methods correspond, i.e. 5-30 m for the predicted and 4-27 m for the measured. This suggests that both procedures are about equal in sensitivity to variations in

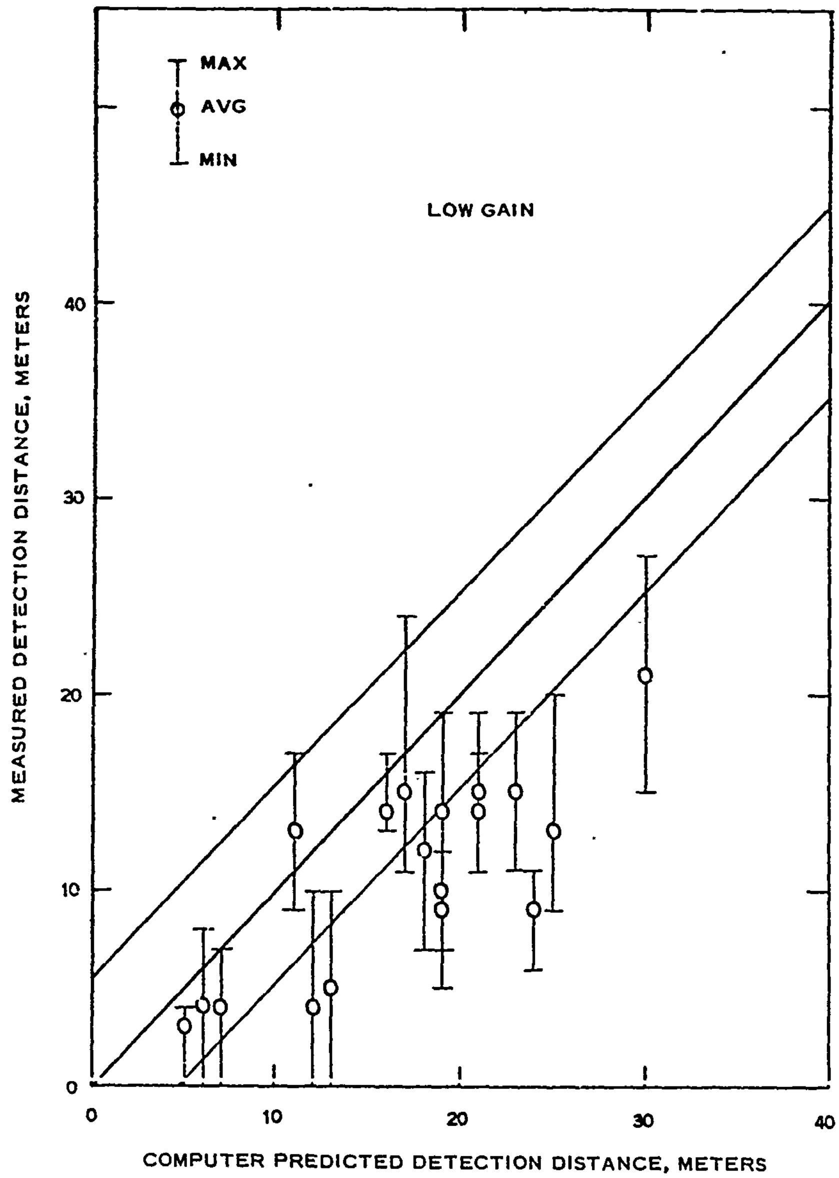

Fig. 4. Predicted analog vs measured detection ranges

site conditions. On the basis of this analysis, it was assumed that the analog computer predictions could be used to estimate the quality of predictions obtained from the digital computer program.

39. The detection ranges determined with the analog computer were used as a reference for evaluating the digital computer program for predicting seismic sensor performance. The detection range values for medium and low gain obtained with the analog computer were plotted against the low- and medium-gain detection ranges predicted by the

digital program for the selected test sites in Panama and Arizona (figs. 5 and 6, respectively).

40. The curves in figs. 5 and 6 show that the techniques used for

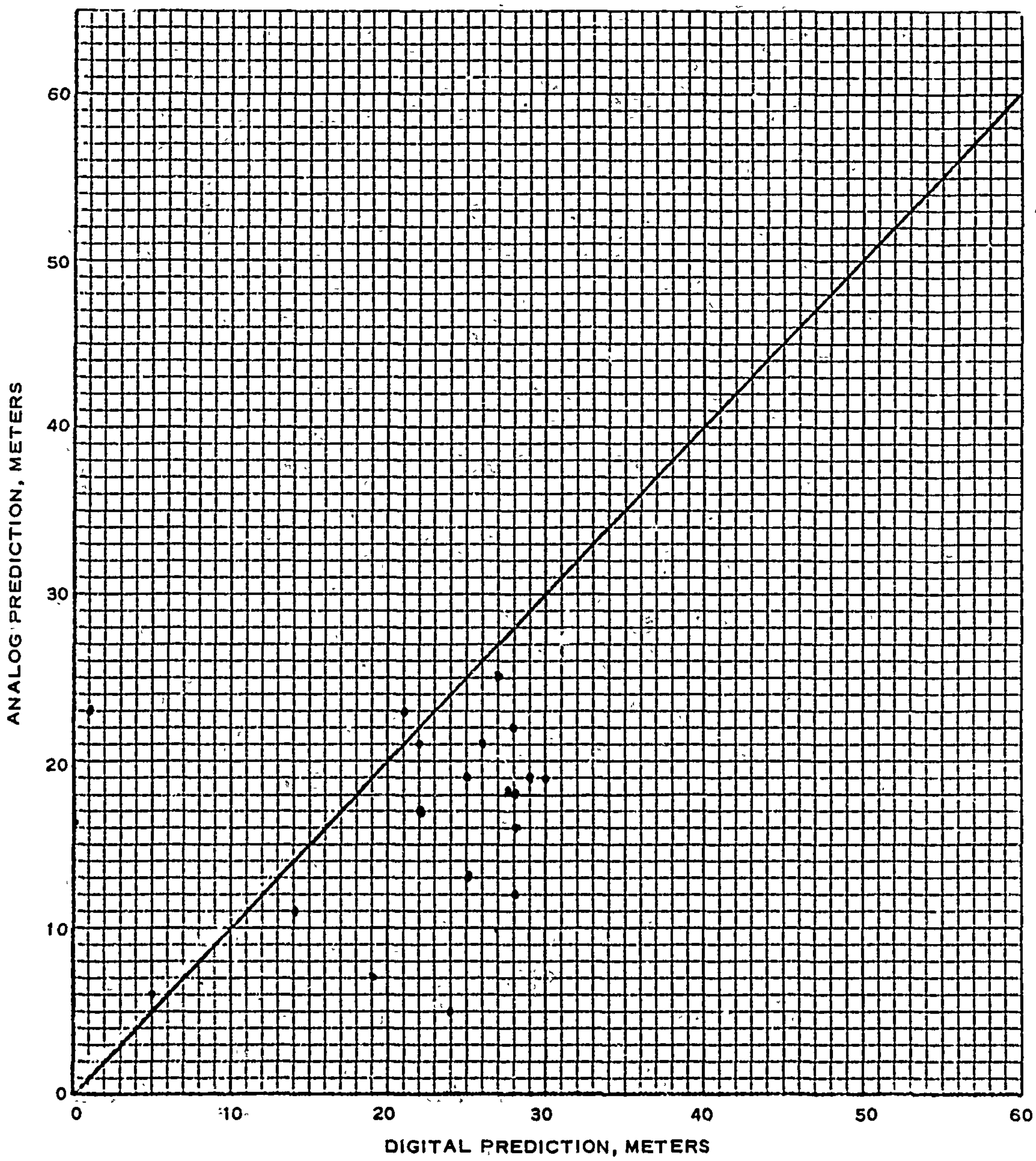

Fig. 5. Comparison of analog and digital predictions of sensor performance, low gain

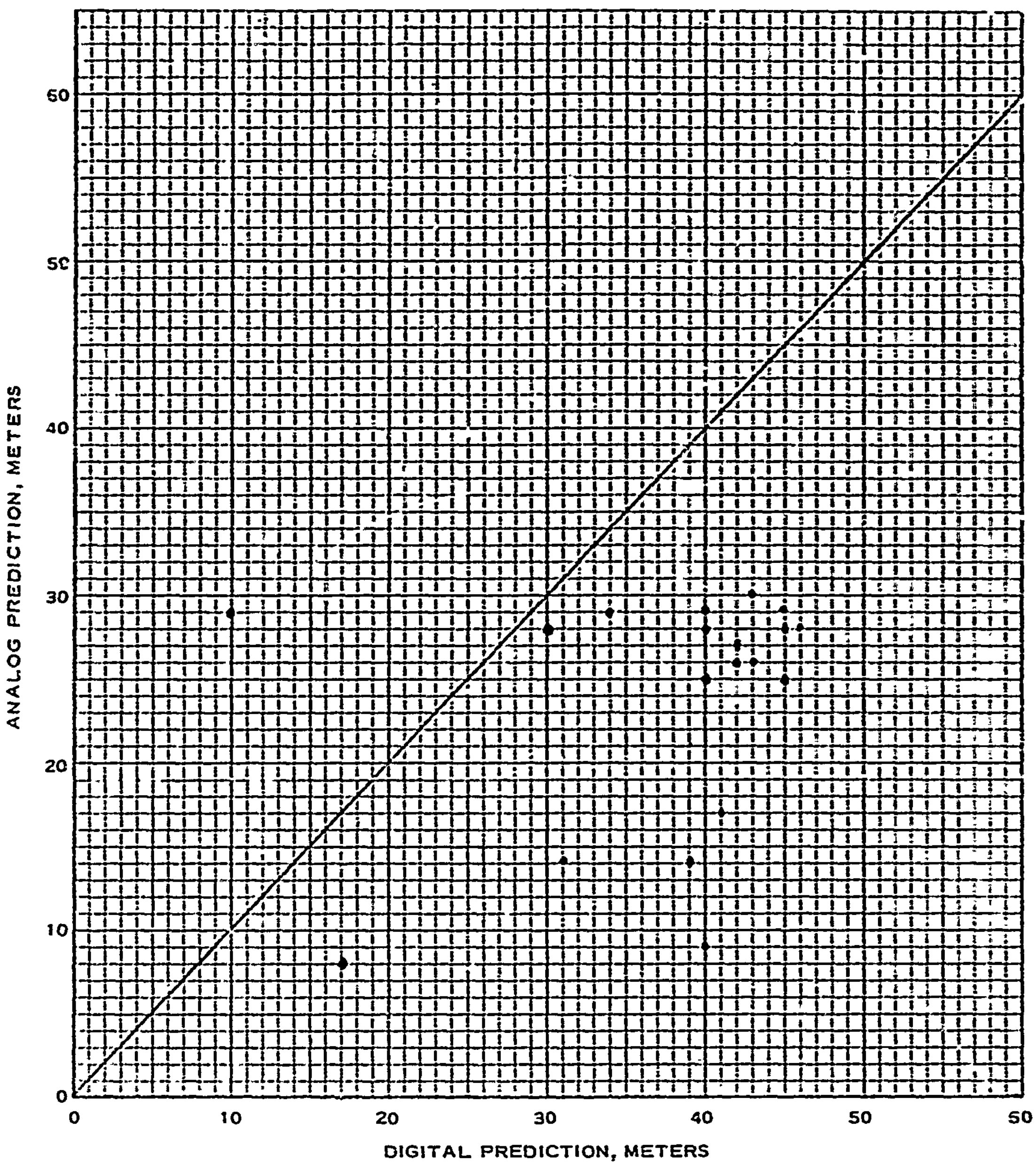

Fig. 6. Comparison of analog and digital predictions of sensor performance, medium gain

predicting sensor performance are not adequate; the digital computer program predicted values that were in general much higher than the values obtained with the analog computer. The inadequacy of the

predictions may be due to several factors. First, the sensor electronic components look at the entire seismic signal. Thus, the peak particle velocity alone does not convey enough information regarding the characteristics of the seismic signal. Second, the frequency response of the sensor and the frequency characteristics of the seismic signal have been ignored, and these factors are believed to be very significant in predicting sensor performance.

PART III. TERRAIN FACTOR INPUTS

41. The majority of the terrain factors measured during the field data collection were analyzed to determine the highest correlation with the peak particle velocity. For the terrain analyst, however, the best model may be of little value if the input requirements are so stringent that they are virtually unattainable. The equation used for the digital computer sensor performance model was selected on the basis of the relative ease of acquisition of the input values.

42. A total of nine terrain factors are required for the present version of the model. These terrain factors are listed in paragraph 26. The ideal way to obtain the input values is by direct measurement or calculation. Often access to the ground is denied and the terrain factor inputs will have to be estimated. This estimation will often have to be made from aerial photographs; various soils, geologic, physiographic, or land use maps; and other literature. This part of the report presents data that can be used as an aid in estimating the terrain factor value. This information is not complete, and the terrain analyst should supplement it with information from other sources.

Estimating Cone Index, Soil Type, and Water Content Values

43. The cone index value of a soil is a function of soil type (Unified Soil Classification System (USCS)) and soil moisture content. The type of the surface soil can often be estimated reliably from aerial photographs or soil maps (see reference 6). In general, the water content of a soil cannot be readily estimated from remote sensing imagery, visible photography, or most soils maps since it is a function of rainfall, topographic position, soil type, and other factors related in a complex manner. Automation of a soil moisture prediction model being developed at the WES is scheduled for completion in June 1972, thus providing a means for estimating average daily soil moisture content. If soil type and water content are known, cone index values for the 0- to 15-cm layer can be estimated from the generalized relations among soil

type, moisture content, and cone index shown in fig. 7.[7] Additional data on the relation of cone index, soil type, and water content are given in reference 8.

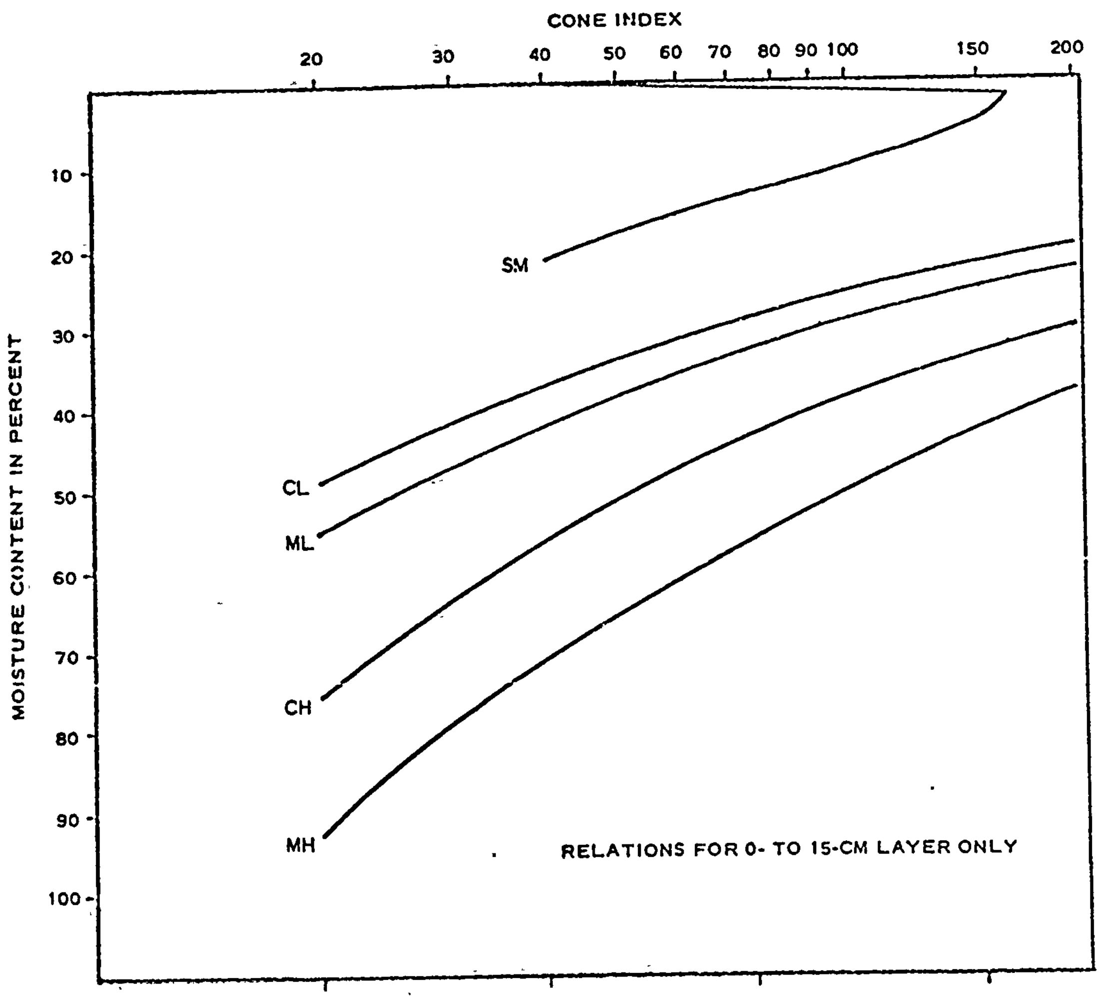

Fig. 7. Generalized relations among soil type (after reference 7), soil moisture content, and cone index

44. Aids for estimating surface cone index are not readily available, but probably could be developed from existing data at the WES. Surface cone index values are often 30 to 50% of the average cone index of the 0- to 15-cm layer, but values 10% of the cone index of the 0- to 15-cm layer are common.

Estimating Dry Density and Layer Thickness Values

Dry density

45. Values of mean dry density for USCS soil types[8] are listed below.

USCS Type	Mean Dry Density g/cm³
SM-SC	1.62
SC	1.60
SP-SM	1.57
SM	1.50
CL-ML	1.49
CL	1.46
ML	1.37
CH	1.36
OL	1.32
MH	1.11
OH	1.00

These density values were derived from analysis of approximately 1300 samples taken from the 15- to 30-cm layer in the temperate zone. Normally the 0- to 15-cm layer contains more organic matter and will exhibit slightly less dry density, i.e. values from 10 to 15% less than those shown. Fig. 8 is presented to allow estimation of dry density from known in situ moisture content.[9]

Thickness of the first soil layer

46. This terrain factor value is probably the most difficult to obtain by noncontact means. Estimates of soil thickness can often be made by photo interpretation and study of the geologic land use, soil maps, and related literature of the area. As previously mentioned, however, these estimates may not be valid for seismic layers that are based on physical soil properties.

Estimating Compression Wave Velocity

47. The terrain analyst, having determined soil or rock type, can obtain estimates of compression wave velocities from the following tabulation.

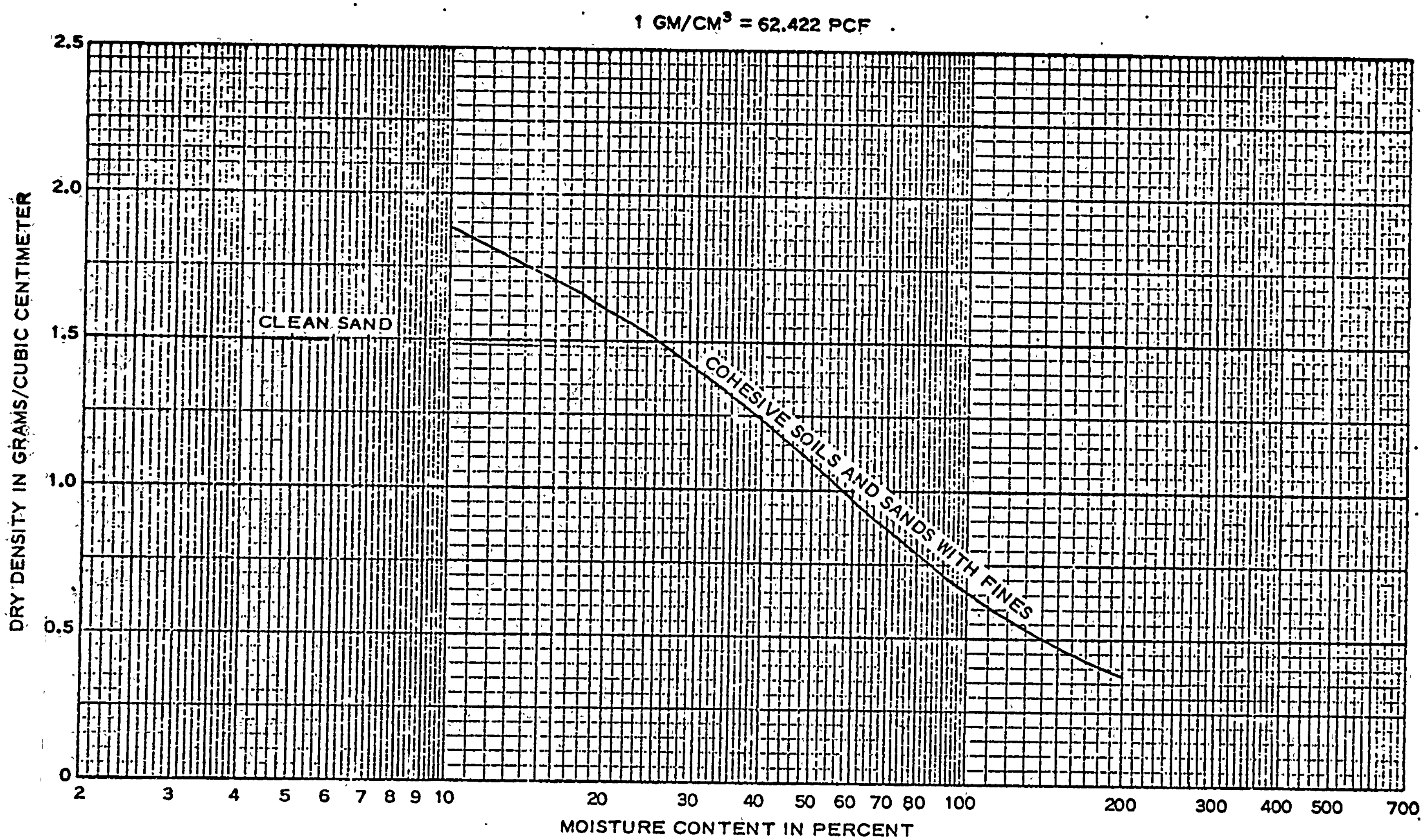

Fig. 8. Dry density as a function of field moisture content, 0- to 15-cm layer (reference 9)

Soil or Rock Types	Estimated Compression Wave Velocity m/sec
Dry, loose topsoils and silts	180 to 365
Dry sands, loams, and slightly sandy or gravelly soft clays	300 to 485
Dry gravels; moist sandy and gravelly soils	450 to 910
Dry, heavy gravelly clay; moist heavy clays; cobbly materials with considerable sands and fines; soft shales; soft or weak sandstones	910 to 1450
Water; saturated silts or clays; wet gravels	1460 to 1524
Compacted moist clays; saturated sands and gravels; soils below the water table; dry medium shales; moderately soft sandstones; weathered moist shales and schists	1460 to 1829
Hardpan; cemented gravels; hard clay; boulder till; compact cobbly and bouldery materials; medium to moderately hard shales and sandstones; partially decomposed granites; jointed and fractured hard rocks	1676 to 2438
Hard shales and sandstones; interbedded shales and sandstones; slightly fractured limestones and crystalline rocks	2438 to 3657
Unweathered limestones, granites, gneiss, and other dense rocks	3657 to 6100

Rayleigh Wave Velocity

48. Rayleigh wave velocity is equivalent to shear wave velocity. For very rough estimates, Rayleigh wave velocity can be assumed to be 40 percent of the compression wave velocity.

PART IV: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

49. Results to date in the WES seismic sensor programs indicate that terrain factors can be correlated with the seismic response characteristics of an area. These correlations can then be used to predict the peak amplitude of a seismic signal with distance; however, prediction of seismic sensor performance by this method is by no means adequate. Although the present version of the computer program is inadequate for predicting SID performance, it can be easily updated, and an improved prediction capability can be expected as additional information becomes available and additional analyses are completed.

50. Although the predicted peak particle velocity-distance curves are not adequate to allow accurate determinations of sensor performance, they may be used with confidence (within the range of experimental data upon which they are based) to obtain a relative comparison of the seismic response characteristics of difference areas.

51. The terrain factor values required as inputs to the computerized model are those that are common to the earth sciences. Considerable data in various parts of the world have been collected on these terrain factors, and reasonable estimates of their values can be made on the basis of literature and other information sources, such as remote sensing products and the WES soil moisture prediction system.

Recommendations

52. Continued work on the development of an analytical procedure for predicting SID performance is recommended. Emphasis should be placed on developing theoretical equations for predicting the complete particle velocity wave train as a function of distance. Computer routines capable of interpreting the particle velocity wave train in a manner analogous to that of the sensor should be developed. These sensor simulation routines should be combined with the theoretical wave

propagation equations to provide a theoretically based SID performance model.

53. Additional research should be conducted to develop improved techniques for obtaining the terrain factor input values.

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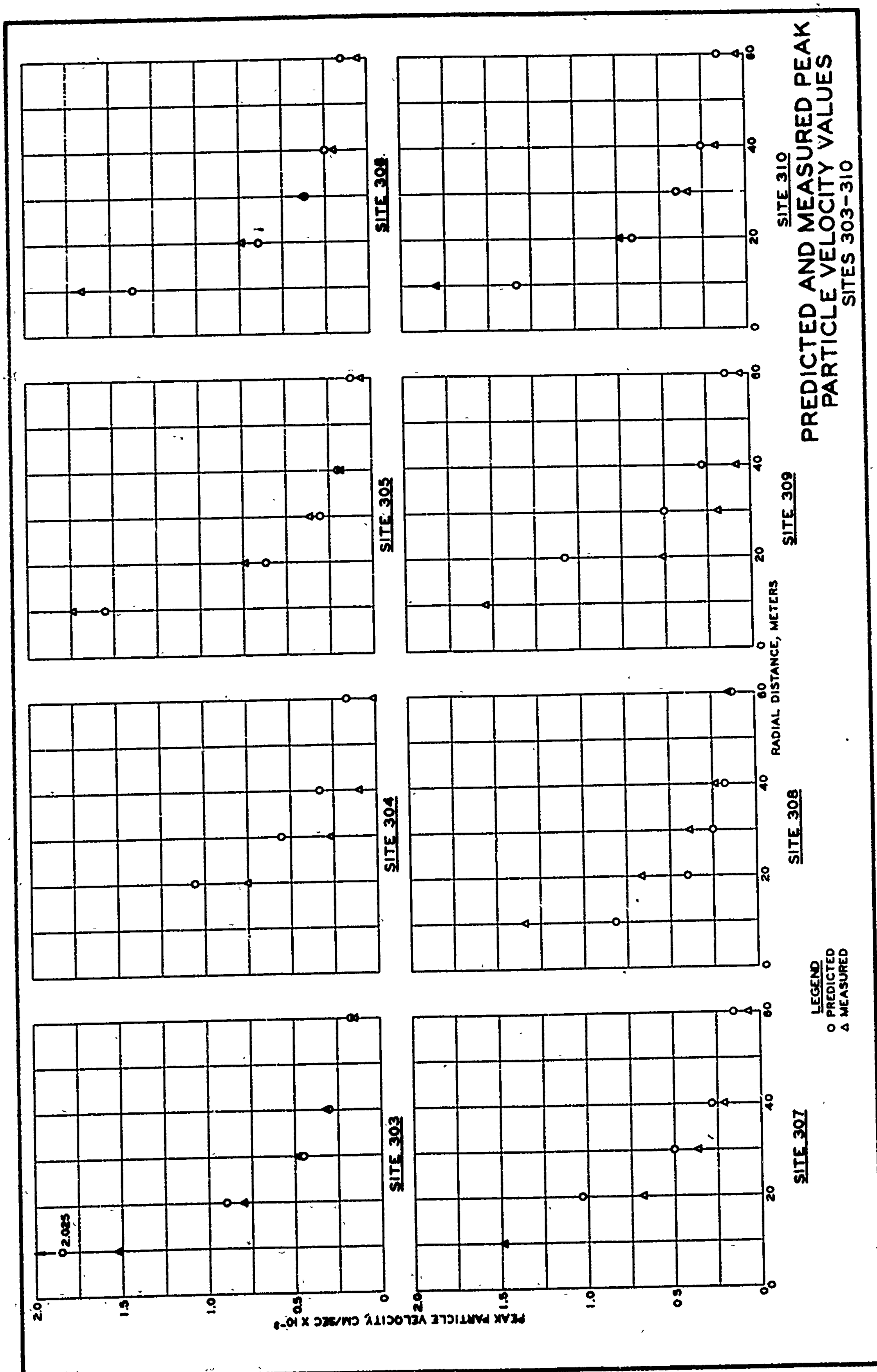
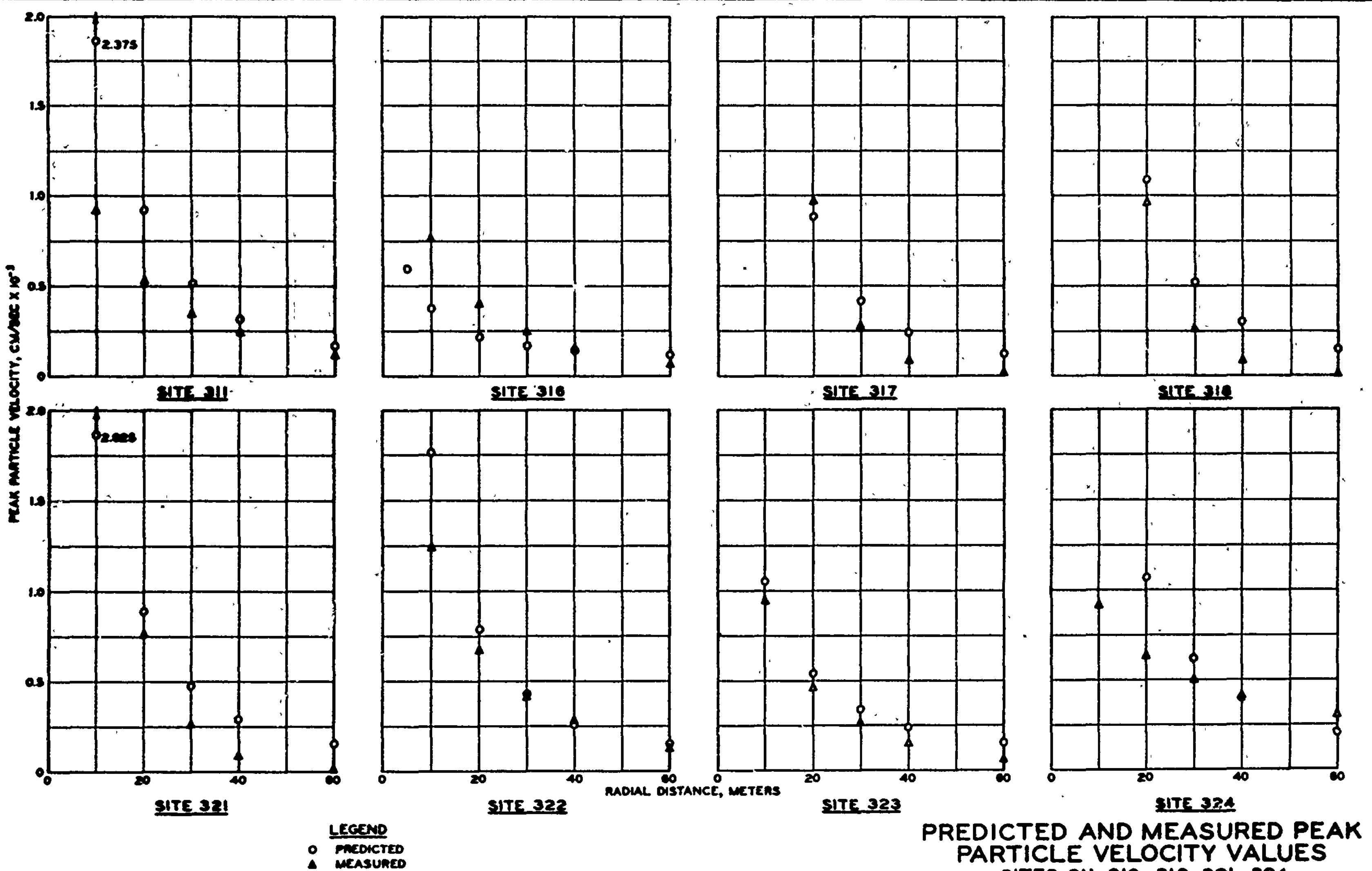


PREDICTED AND MEASURED PEAK
PARTICLE VELOCITY VALUES
SITES 303-310
SITE 303
SITE 304
SITE 305
SITE 306
SITE 307
SITE 308
SITE 309
SITE 310
PEAK PARTICLE VELOCITY, CM/SEC X 10^-3
RADIAL DISTANCE, METERS
2.085
LEGEND
O PREDICTED
Δ MEASURED

PLATE 1

PLATE 2



PREDICTED AND MEASURED PEAK PARTICLE VELOCITY VALUES
SITES 311, 316-318, 321-324

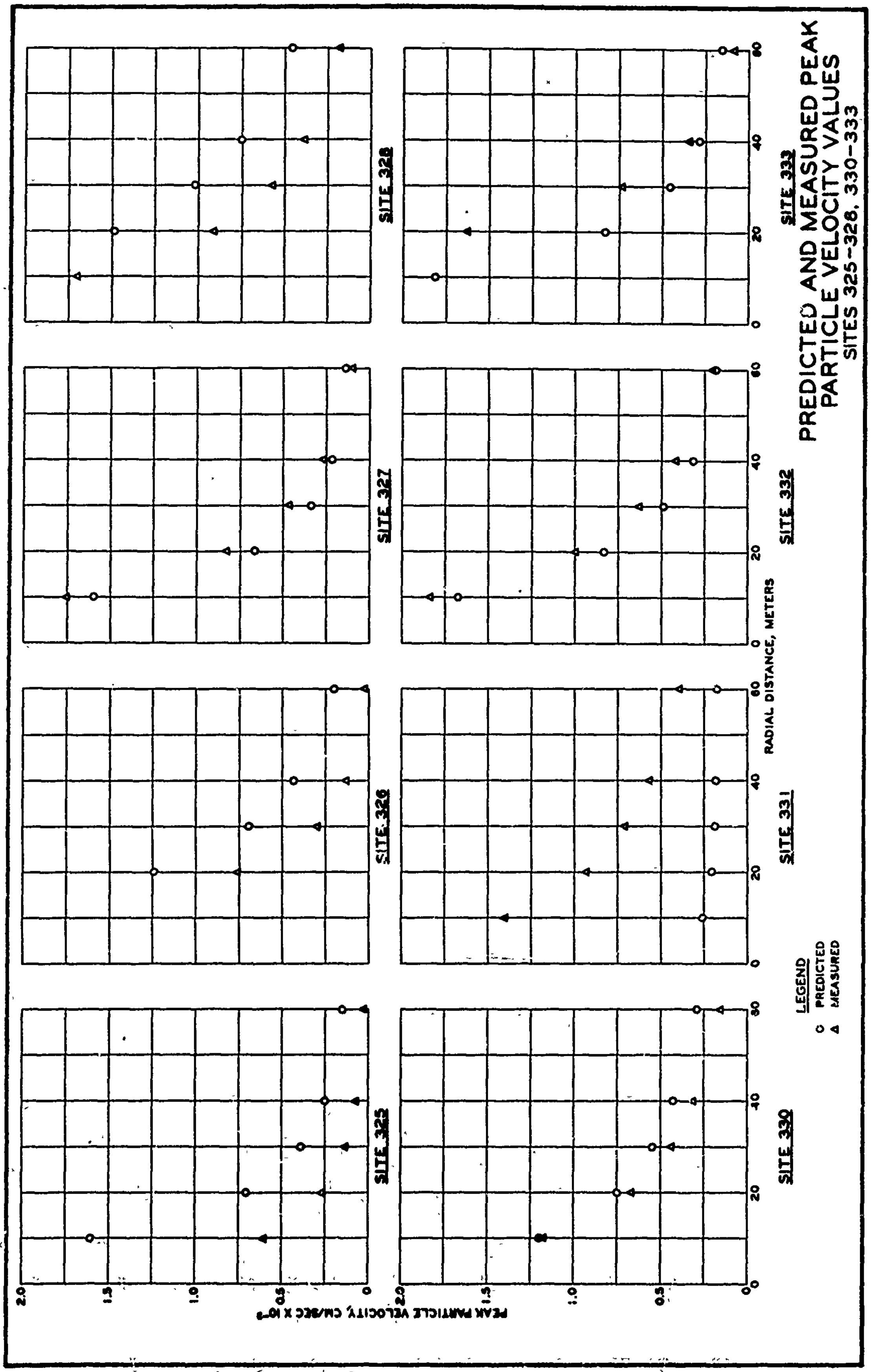

PREDICTED AND MEASURED PEAK
PARTICLE VELOCITY VALUES
SITES 325–328, 330–333
SITE 325
SITE 326
SITE 327
SITE 328
SITE 330
SITE 331
SITE 332
SITE 333
PEAK PARTICLE VELOCITY, CM/SEC X 10⁻³
RADIAL DISTANCE, METERS
LEGEND
○ PREDICTED
△ MEASURED

PLATE 3

APPENDIX A: COMPUTER PROGRAM TO PREDICT SID DETECTION DISTANCE*

Description of Function and Method

1. A computer program has been developed to estimate detection distance (in the program detection distance is termed detection radii) from one man walking to a seismic sensor as a function of soil parameters. The program is intended to be self-instructive, easy to learn to use, and, since it operates in the conversational mode, suited to processing of relatively small quantities of data input from a teletype. The peak particle velocity-distance equation, described in the main text, is computed in a subroutine so that it can be revised with little change in the main program.

2. The values of the peak particle velocity (resulting from a hammer drop**) are computed for radii of 2, 5, 10, 15, 20, 30, and 40 m. If the computed peak particle velocity becomes zero or negative at a radius of less than 40 m, velocity values corresponding with greater radii are ignored. The array of values for radius vs peak particle velocity is entered into a spline curve-fitting routine (subroutine SPL), which generates a peak particle velocity for each meter of radius from 2 to 40 m. These values are written into a disc file (fig. A1).

3. After the spline routine is completed, the resulting array enters a subroutine called PRED, in which the peak particle velocities required to open the sensor logic at medium- and low-gain settings are found. The radius associated with the selected peak particle velocity becomes the predicted detection radius. If the associated radius exceeds 40 m, the solution is not valid, and the value of the associated radius is set to zero.

---

* This program is furnished by the Government and is accepted and used by the recipient with the express understanding that the United States Government makes no warranties, expressed or implied, concerning the accuracy, completeness, reliability, usability, or suitability for any particular purpose of the information and data contained in this program or furnished in connection therewith, and the United States shall be under no liability whatsoever to any person by reason of any use made thereof. The program belongs to the Government. Therefore, the recipient further agrees not to assert any proprietary rights therein or to represent this program to anyone as other than a Government program.

** Equivalent to a footstep.

Description of Input and Output

Input variables

Record	Variable Name	Column(s)	Mode	Units	Description
1	C115	Free-field	Floating	Dimensionless	Cone index (0- to 15-cm layer)
	WC	Free-field	Floating	Dimensionless	Water content of surface
	WC1	Free-field	Floating	Dimensionless	Water content of first layer
	VP	Free-field	Floating	m/sec	Compression wave velocity
	VR	Free-field	Floating	m/sec	Rayleigh wave velocity
	H	Free-field	Floating	m	Thickness of first seismic layer
	PFS	Free-field	Floating	Dimensionless	Percent fines decimal
	GAMD	Free-field	Floating	gm/cc	Dry density of surface
	GAMD1	Free-field	Floating	gm/cc	Dry density of first layer
2	ANAM	1-6	A	--	Site identification alphanumeric characters
3	NAME	1-6	A	--	Name of saved file into which to write results of equation
4	XO	Free-field	Floating	m	Initial radius
	XMAX	Free-field	Floating	m	Maximum radius
	DELX	Free-field	Floating	m	Spline fit increment desired

Output

4. An example of the output from program KLN012 with teletype input of soil parameters is shown in fig. A2. Circled numbers in the left margin correspond to the input record order in the input description above.

Operating Instructions

5. Save the names of the output files. If no plots of radius

versus peak particle velocity are desired, the same name may be used for several sites.

6. Run the program. Data must be entered from the keyboard as shown in fig. A2 when it is requested by the program.

Program Listings

7. The program listing is shown in fig. A3. The language used is FORTRAN IV adapted for use on a G-437 (Honeywell) time-sharing computer.

Flow Charts

8. The flow charts of the main program and necessary subroutines are presented in plates A1 and A2.

NAM1 INCREMENT	DISTANCE (M)	PEAK PARTICLE VELOCITY (CM/SEC × 10^{-3})
00001 TEST		
00002	2.000	12.743
00003	3.000	10.438
00004	4.000	8.307
00005	5.000	6.522
00006	6.000	5.268
00007	7.000	4.424
00008	8.000	3.880
00009	9.000	3.526
00010	10.000	3.253
00011	11.000	2.979
00012	12.000	2.690
00013	13.000	2.403
00014	14.000	2.130
00015	15.000	1.889
00016	16.000	1.687
00017	17.000	1.523
00018	18.000	1.389
00019	19.000	1.276
00020	20.000	1.178
00021	21.000	1.087
00022	22.000	1.003
00023	23.000	0.925
00024	24.000	0.852
00025	25.000	0.785
00026	26.000	0.724
00027	27.000	0.668
00028	28.000	0.617
00029	29.000	0.570
00030	30.000	0.529
00031	31.000	0.491
00032	32.000	0.458
00033	33.000	0.429
00034	34.000	0.402
00035	35.000	0.378
00036	36.000	0.357
00037	37.000	0.337
00038	38.000	0.319
00039	39.000	0.301
00040	40.000	0.284

Fig. A1. Peak particle velocity values generated by the spline curve-fitting routine

```
RUN

KLN012    14:23  WES   01/26/72

ENTER STOP IF YOU WISH TO STOP THE PROGRAM
INPUT ON FIRST LINE, SEPARATING THE VARIABLES BY COMMAS,
THE FOLLOWING VARIABLES:(1)CONE INDEX(0-15 CM),
(2)WATER CONTENT OF SURFACE, (3)WATER CONTENT OF FIRST LAYER,
(4)COMPRESSION WAVE VELOCITY(M/SEC), (5)RAYLEIGH WAVE VELOCITY (M/SEC),
(6)THICKNESS OF FIRST SEISMIC LAYER(CM),(7) PERCENT FINES(%),
(8) DRY DENSITY OF SURFACE(GM/CC),(9) DRY DENSITY OF FIRST LAYER(GM/CC)

ON SECOND LINE ENTER UP TO SIX CHARACTERS OF IDENTIFICATION

(1) ?120.,.38,.45,351.,134.,488.,82.,.82,1.1
(2) ?TEST

ENTER FILE NAME INTO WHICH TO WRITE SPLINE VALUES
(3) ?NAM1

COMPUTED VALUES OF R VS. UDH
  SITE  TEST

      R        UDH
    2.000    12.743    1
    5.000     6.522    2
   10.000     3.253    3
   15.000     1.889    4
   20.000     1.178    5
   30.000     0.529    6
   40.000     0.284    7
ENTER INITIAL R AND MAXIMUM R FROM ABOVE TABLE,AND
INCREMENT OF SPLINE VALUES DESIRED(USUALLY 1)
(4) ?2,40,1

          DETECTION RADII FOR SITE TE
             MEDIUM          LOW GAIN
               0.            37.
```

Fig. A2. Sample run of program KLN012

KLN012

```
1STTY,120
2SNOM
110C THIS PROGRAM USES ONE OR TWO EQUATIONS TO PREDICT DETECTION RADII
120C  OF A SENSOR AT THREE DIFFERENT GAIN SETTINGS
130 DIMENSION R(7),UDH(7),UDH2(7)
135 EQUIVALENCE (UDH,UDH2)
140 REAL NAME
150C  THESE DATA ARE THE RADII FOR WHICH UDH VALUES ARE COMPUTED
160 DATA R/2.,5.,10.,15.,20.,30.,40./
165 DATA TEMP/"      "/
190 10 CONTINUE
240 51 FORMAT("INPUT ON FIRST LINE, SEPARATING THE VARIABLES BY COMMAS,"
250&/"THE FOLLOWING VARIABLES:(1)CONE INDEX(0-15 CM),
252&"/"
255&(2)WATER CONTENT OF SURFACE, (3)WATER CONTENT
260&OF FIRST LAYER,"/"(4)COMPRESSION WAVE VELOCITY(M/SEC).
265& (5)RAYLEIGH WAVE VELOCITY (M/SEC),"/"(6)THICKNESS OF FIRST SEISMIC
266&
270&LAYER(CM),(7) PERCENT FINES(%),"/"(8) DRY DENSITY OF
280& SURFACE(GM/CC),(9) DRY DENSITY OF FIRST LAYER(GM/CC)"
285&//"ON SECOND LINE ENTER UP TO SIX CHARACTERS OF IDENTIFICATION"//)
290 PRINT,"ENTER STOP IF YOU WISH TO STOP THE PROGRAM
291&"
295 295 PRINT 51
300 149 READ,CI15,WC,WC1,VP,VR,H,PFS,GAMD,GAMD1
305 READ 306,ANAM
306 306 FORMAT(A6)
312 IF(ANAM.EQ.6HSTOP  )CALL EXIT
320 320 PRINT,"ENTER FILE NAME INTO WHICH TO WRITE SPLINE VALUES"
330 READ 154,NAME
340 154 FORMAT(A6)
400 30 CALL THREE(CI15,WC,WC1,VP,VR,H,PFS,GAMD,GAMD1,UDH,R)
420C  SOLVE FOR SELECTED VALUES OF UDH
560 K1=J-1
570 160 DO 250 I=1,7
580 IF(UDH2(I))170,170,250
590 170 K2=I
600 UDH2(I)=0.
610X 267 FORMAT(2(I5,2F10.2))
620 GOTO 260
630 250 CONTINUE
640 K2=I-1
645 260 CONTINUE
660 660 CONTINUE
670 283 FORMAT("COMPUTED VALUES OF R VS. UDH"/
680&2X,"SITE",2X,A6//7X,"R",6X,"UDH"/(2F10.3,I5))
690 PRINT 283,ANAM,(R(IZ),UDH(IZ),IZ,IZ=1,K2)
720 293 CALL SPL(K2,R,UDH,3,NAME,ANAM,KNT2)
730 CALL PRED(3,NAME,KNT2)
740 GO TO 10
```

Fig. A3. Listing of program KLN012

XLNO12 CONTINUED

```
750 888 STOP 888
760 END
1080 SUBROUTINE PRED(NDEV,NAME,KNT)
1090C THIS ROUTINE COMPARES VALUES FOR LOW, MEDIUM, AND HIGH GAIN
1100C   TO VALUES ON THE R VS. UDH CURVE.
1110 DIMENSION R(100),UD(100),FR(3)
1120 DIMENSION DRAD(3)
1130 DATA FR/.1,.2,0.5/
1140 CALL OPENF(NDEV,NAME)
1150 READ(NDEV,826),ANAM
1160 826 FORMAT(A6
1170&)
1180 DO 662 I=2,3
1190 662 DRAD(I)=0.
1200 READ(NDEV,829)(R(I),UD(I),I=1,KNT)
1210 829 FORMAT(2F10.3)
1220 DO 150 L=2,3
1230 DO 50 J=1,KNT
1240 IF(FR(L)-UD(J))50,100,100
1250 50 CONTINUE
1270 GO TO 150
1280 100 DRAD(L)=R(J)
1290 150 CONTINUE
1295 PRINT 1296,ANAM
1296 1296 FORMAT(10X,"DETECTION RADII FOR SITE",1X,A2)
1300 PRINT 1301
1301 1301 FORMAT(13X,"MEDIUM",10X,"LOW GAIN")
1310 PRINT 1311,(DRAD(K),K=2,3)
1311 1311 FORMAT(5X,2F13.0)
1320 PRINT 1321
1321 1321 FORMAT(////)
1330 CALL CLOSEF(NDEV)
1340 790 RETURN
1350 END
1360 SUBROUTINE SPL(N,X,Y,NDEV,NAME,ANAM,KNT)
1370C     SPLINE TEST PROGRAM BY J CHEEK, ADPC
1380      DIMENSION X(100),Y(100),TORGUE(100)
1390XPRINT 836,NDEV,NAME
1400 836 FORMAT(I5,A6)
1410 CALL OPENF(NDEV,NAME)
1420 KNT=0
1430    10 CONTINUE
1440      CALL SPLINE (X, Y, N, TORQUE)
1450XPRINT,"WE ARE NOW IN THE SPLINE ROUTINE"
1460 PRINT,"ENTER INITIAL R AND MAXIMUM R FROM ABOVE TABLE,AND"
1465 PRINT,"INCREMENT OF SPLINE VALUES DESIRED(USUALLY 1)"
1470 WRITE(NDEV,157),ANAM
1480 157 FORMAT(A6)
1490      READ, X0,XMAX, DELX
1500  100 CONTINUE
```

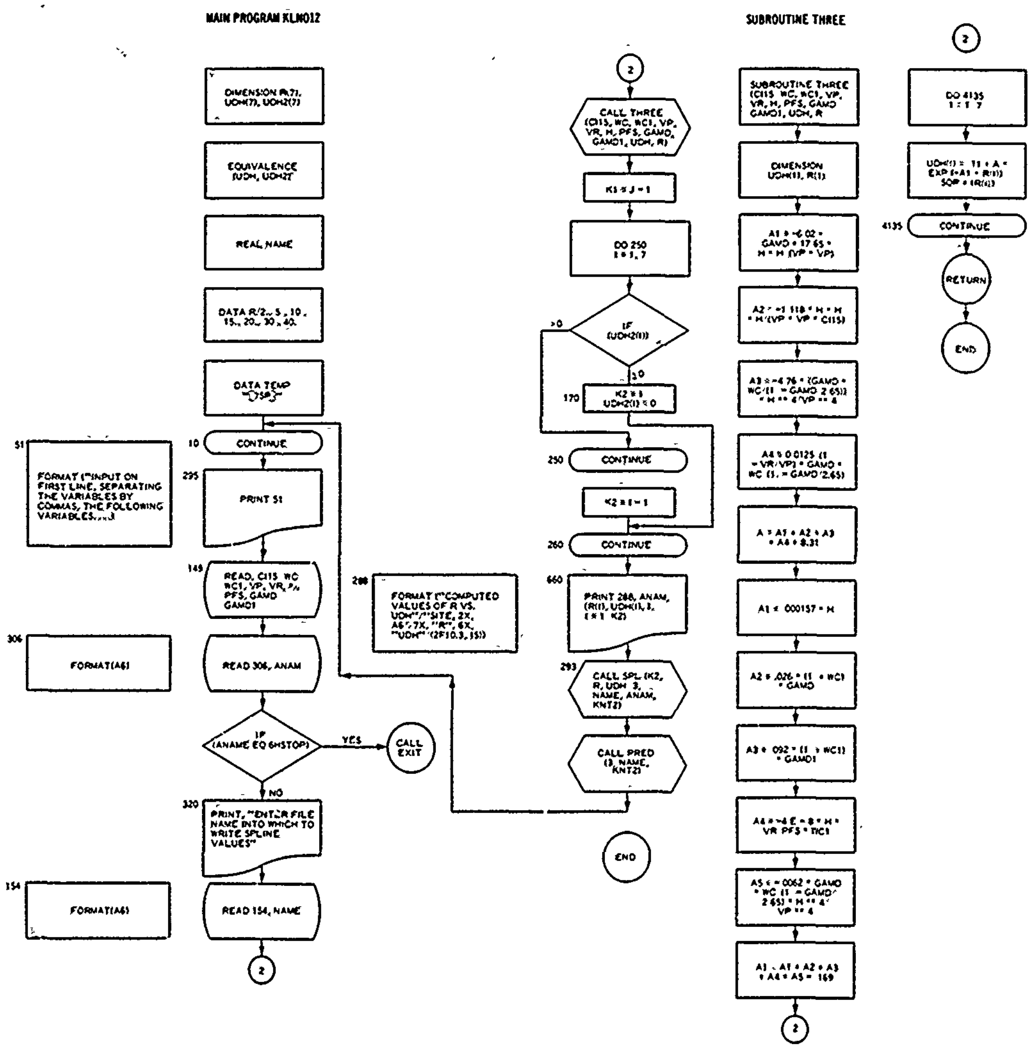
KLNC12 CONTINUED

```
CALL SPLINT(X0,YY,YYP,YYPP,X,Y,TORQUE,N,IND,J)
WRITE(NDEV,120)X0,YY
KNT=KNT+1
120 FORMAT(2F10.3)
    X0 = X0 + DELX
IF(X0.GT.XMAX) GO TO 110
GO TO 100
110 CONTINUE
CALL CLOSEF(NDEV)
RETURN
 END
SUBROUTINESPLINE(X,Y,N,S2)
DIMENSION X(1),Y(1),S2(1)
DATAEPSLN/1./
N1 = N - 1
ASSIGN54TOISW
DO59I=1,N1
H=X(I+1)-X(I)
DLY=(Y(I+1)-Y(I))/H
GOTOISW,(54,53)
53H2ZZZ=HL+H
    S2(I) = 2. * (DLY - YL) / H2ZZZ
GOTO55
54ASSIGN53TOISW
56HL=H
YL=DLY
59CONTINUE
C
S2(1)=0.
S2(N)=0.
OMEGA=-1.0717968
ETA=0.
    ASSIGN 154 TO  ISW1
    DO 10 I=1,N1
H=X(I+1)-X(I)
DLY=(Y(I+1)-Y(I))/H
GO TO ISW1,(154, 153)
153H2ZZZ=HL+H
BI=.5*HL/H2ZZZ
W = (BI * S2(I-1) + (.5 - BI) * S2(I+1) + S2(I)
&   + 3. * (YL - DLY) / H2ZZZ) * OMEGA
S2(I) = S2(I) + W
Z=ABS(W)
154 ASSIGN 153 TO ISW1
156 HL=H
YL=DLY
10 CONTINUE
IF(ETA-EPSLN)14,5,5
14 CONTINUE
RETURN
```

KLN012 CONTINUED

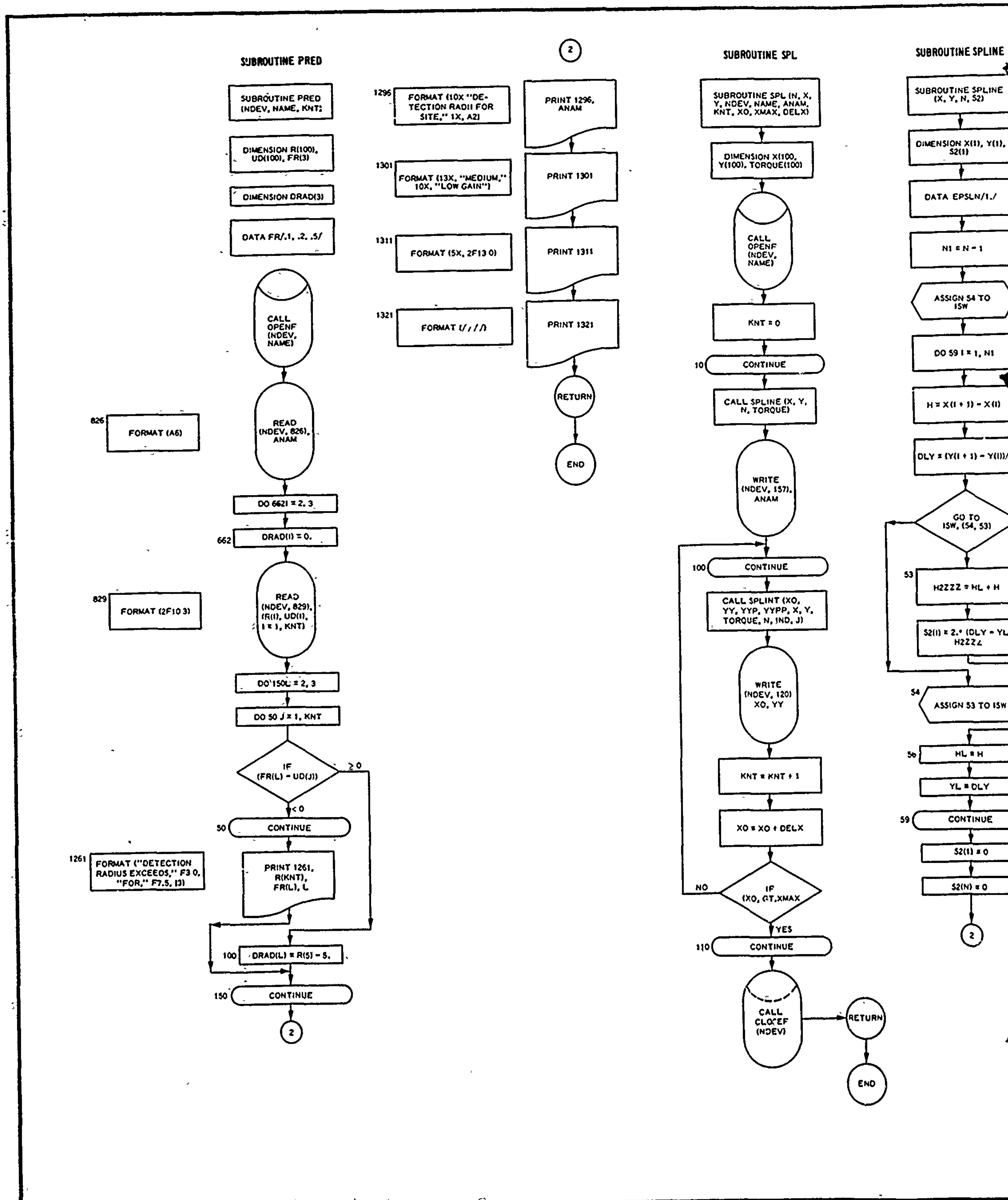
```
2010 END
2020 SUBROUTINESPLINT(XX,FXX,FPXX,FPPXX,
2030&X,Y,S2,N,M,IC)
2040 DIMENSIONX(1),Y(1),S2(1)
2050 M=0
2060 XP=XX
2070 I=1
2080 IF(XP-X(1))52,17,55
2090 52M=-1
2100 XP=X(1)
2110 GOTO17
2120 55IF(XP-X(N))57,59,58
2130 56IF(XP-X(I))60,17,57
2140 57I=I+1
2150 GO TO 56
2160 58 M=-1
2170 XP=X(N)
2180 59 I=N
2190 60I=I-1
2200 17HT1=XP-X(I)
2210 HT2=XP-X(I+1)
2220 PROD=HT1*HT2
2230 DX=X(I+1)-X(I)
2240 DELY=(Y(I+1)-Y(I))/DX
2250 S3=(S2(I+1)-S2(I))/DX
2260 FPPXX=S2(I)+HT1*S3
2270 DELSQS=(S2(I)+S2(I+1)+FPPXX)/6.
2280 FXX=Y(I)+HT1*DELY+PROD*DELSQS
2290 FPXX = DELY + (HT1 + HT2) * DELSQS + PROD * S3 / 6.
2300 IF(M.EQ.0)GOTO100
2310 FXX=FXX+FPXX*(XX-XP)
2320 100CONTINUE
2330 RETURN
2340 END
4000 SUBROUTINE THREE(CI15,WC,WC1,VP,VR,H,PFS,GAMD,GAMD1,UDH,R)
4005 DIMENSION UDH(1),R(1)
4010 A1=-6.02*GAMD+17.65*H*H/(VP*VP)
4020 A2=-1.118*H*H*H/(VP*VP*CI15)
4030 A3=-4.76*(GAMD*WC/(1.-GAMD/2.65))*H**4/VP**4
4040 A4=0.0125/(1.-VR/VP)*GAMD*WC/(1.-GAMD/2.65)
4050 A=A1+A2+A3+A4+8.31
4060 A1=.000157*H
4070 A2=.026*(1.+WC)*GAMD
4080 A3=.092*(1.+WC1)*GAMD1
4090 A4=-4.E-8*H*VR/PFS*WC1
4100 A5=-.0062*GAMD*WC/(1.-GAMD/2.65)
4110&*H**4/VP**4
4120 A1=A1+A2+A3+A4+A5-.169
4125 DO 4135 I=1,7
4130 UDH(I)=.11+A*EXP(-A1*R(I))/SQRT(R(I))
```

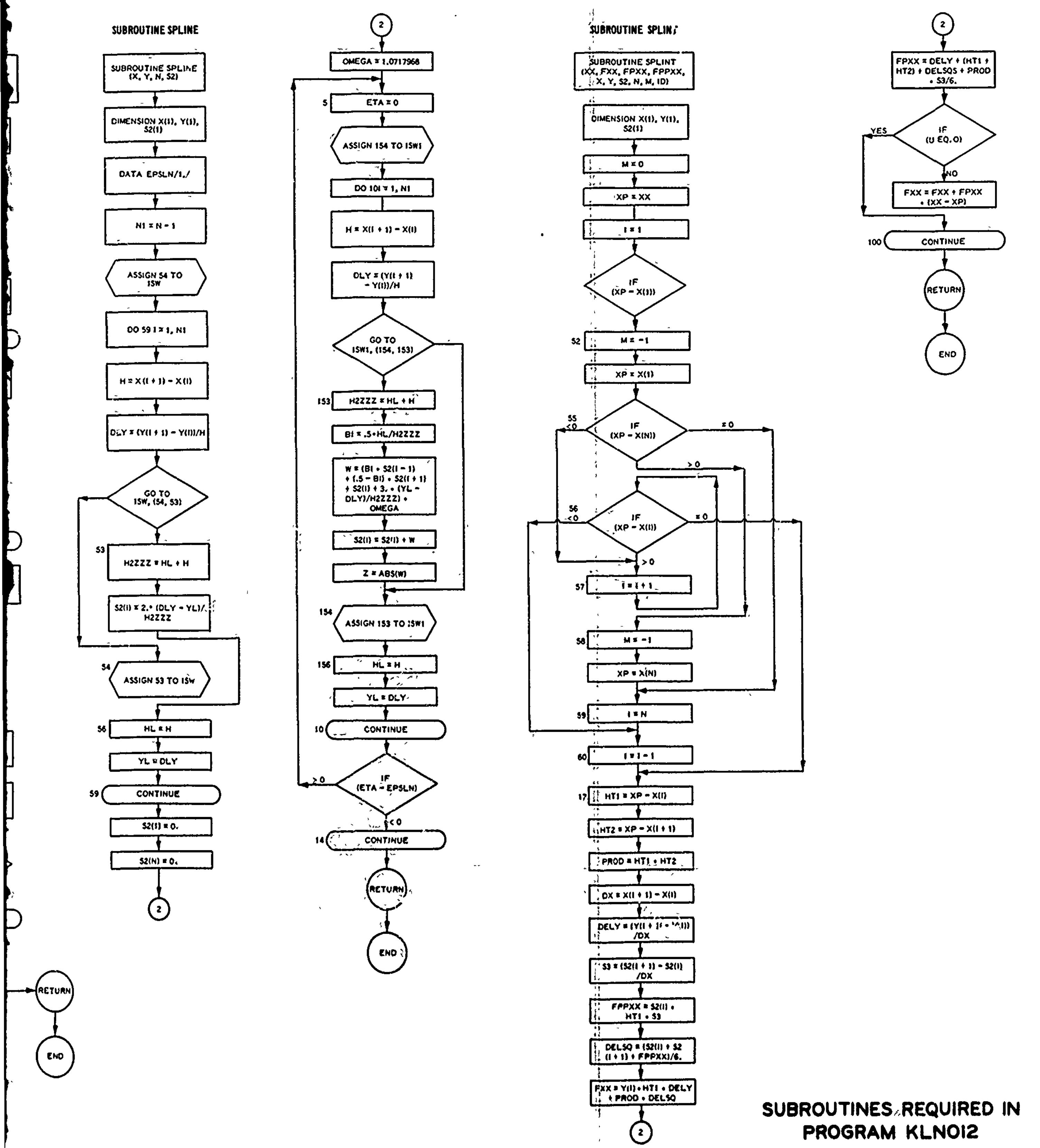
```
XLN012 CONTINUED

4135 4135 CONTINUE
4199 RETURN
4200 END
```



PROGRAM KLN012

PLATE A1


SUBROUTINE PRED
SUBROUTINE PRED (NDEV, NAME, KNT)
DIMENSION R(100), UD(100), FR(3)
DIMENSION DRAD(3)
DATA FR/.1, .2, .5/
CALL OPENF (NDEV, NAME)
826 FORMAT (A6)
READ (NDEV, 826), ANAM
DO 662 I = 2, 3
662 DRAD(I) = 0.
829 FORMAT (2F10 3)
READ (NDEV, 829), (R(I), UD(I), I = 1, KNT)
DO 150 L = 2, 3
DO 50 J = 1, KNT
IF (FR(L) - UD(J))
≥ 0
< 0
50 CONTINUE
1261 FORMAT ("DETECTION RADIUS EXCEEDS," F3 0, "FOR," F7.5, I3)
PRINT 1261, R(KNT), FR(L), L
100 DRAD(L) = R(5) - 5.
150 CONTINUE
2
1296 FORMAT (10X "DETECTION RADII FOR SITE," 1X, A2)
1301 FORMAT (13X, "MEDIUM," 10X, "LOW GAIN")
1311 FORMAT (5X, 2F13 0)
1321 FORMAT (////)
PRINT 1296, ANAM
PRINT 1301
PRINT 1311
PRINT 1321
RETURN
END
SUBROUTINE SPL
SUBROUTINE SPL (N, X, Y, NDEV, NAME, ANAM, KNT, XO, XMAX, DELX)
DIMENSION X(100, Y(100), TORQUE(100)
CALL OPENF (NDEV, NAME)
KNT = 0
10 CONTINUE
CALL SPLINE (X, Y, N, TORQUE)
WRITE (NDEV, 157), ANAM
100 CONTINUE
CALL SPLINT (XO, YY, YYP, YYPP, X, Y, TORQUE, N, IND, J)
WRITE (NDEV, 120) XO, YY
KNT = KNT + 1
XO = XO + DELX
IF (XO, GT, XMAX
NO
YES
110 CONTINUE
CALL CLOSEF (NDEV)
RETURN
END
SUBROUTINE SPLINE
SUBROUTINE SPLINE (X, Y, N, S2)
DIMENSION X(1), Y(1), S2(1)
DATA EPSLN/1./
N1 = N - 1
ASSIGN 54 TO ISW
DO 59 I = 1, N1
H = X(I + 1) - X(I)
DLY = (Y(I + 1) - Y(I))/H
GO TO ISW, (54, 53)
53 H2ZZZ = HL + H
S2(I) = 2.* (DLY - YL)/ H2ZZZ
54 ASSIGN 53 TO ISW
56 HL = H
YL = DLY
59 CONTINUE
S2(1) = 0
S2(N) = 0
2



SUBROUTINES REQUIRED IN PROGRAM KLN012

PLATE A2

2

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11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY U. S. Army Engineer Topographic Laboratories Fort Belvoir, Virginia

13. ABSTRACT

Improved guidance manuals for planning the deployment and emplacement of seismic intrusion detectors (SID's) are needed to optimize the use of these devices for battlefield surveillance. The development of these Military Geographic Intelligence (MGI) products requires a detailed understanding of the operating principles of the detector coupled with an equally detailed understanding of the interactions of the sensor propagation mode with the operational environment. This report presents the results of a preliminary analysis of data collected in a wide range of environments at 22 sites in Panama, 10 sites in Puerto Rico, 6 sites near Yuma Proving Ground, Arizona, and 9 sites near Ft. Huachuca, Arizona. Multiple regression techniques were used to determine the terrain factors that could be correlated with the seismic responses resulting from a man walking or a controlled source (drop hammer) that simulated the signature resulting from a footstep. The measure of seismic response was peak particle velocity as a function of distance from the source. The terrain factors that correlated best with peak particle velocity were the thickness of the first refraction layer, cone index of the 0- to 15-cm soil layer, dry density of surface soil and first soil layer, water content of surface soil and first soil layer, compression wave velocity, Rayleigh wave velocity, and grain-size distribution. An empirical equation was developed to predict peak particle velocity versus distance as a function of the terrain factors. The particle velocities required to trigger the logic of the Phase III SID's were superimposed on the predicted peak particle velocity curves to arrive at a prediction of sensor performance. These computation procedures were computerized to make a prediction model for relative SID performance as a function of terrain factor values. The empirical prediction equation adequately predicted the peak particle distance relation; however, the predictions of sensor performance were inadequate. The errors in the predictions of sensor performance were attributed to the inadequacy of the peak particle velocity-distance relation to represent the complex interaction of the entire seismic signal and the sensor. Frequency characteristics of the seismic signal and the frequency response characteristics of the sensors also must be considered.

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